Development and Application Analysis of 3D Point Cloud Technology Based on Computer Vision in the Field of Welding Robots

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Abstract. With the increasing automation and intelligence of welding robots, new requirements and higher precision standards have been put forward for the welding process of workpieces with complex structures in various welding environments. Robot vision sensing technology is an important foundation for developing welding processes and advancing welding robots. This paper conducts a comprehensive analysis of the development and application status of three-dimensional(3D) point cloud (PC) technology based on computer vision in the field of welding robots. First, the background and current research progress of 3D-PC technology are introduced. Then the application of 3D-PC technology in welding seam recognition and location is analyzed and reviewed. Then the application of 3D-PC technology in welding seam identification and positioning, and welding seam tracking and trajectory planning of welding robots is analyzed and reviewed. Finally, the importance of 3D-PC technology in promoting the development of welding robots is summarized. This paper can serve as a reference for the development and research of 3D-PC technology in robot visual sensing technology.

Keywords: welding robot, 3D point cloud, three-dimensional vision technology

1 Introduction

As time goes on, automated and intelligent welding robots have gradually replaced manual welding. Traditional industrial robots have been widely used in industrial production environments such as automobiles, aviation, and ships. Although the manual teaching type robot to achieve repetitive welding has met the welding standards, the real-time 3D recognition and positioning of the welding seam, the path tracking of the welding seam, and the automatic detection and adjustment of the welding seam change are still lacking. When welding complex welding seams in the fields of shipbuilding and aerospace, it is impossible to achieve automated and intelligent real-time precise tracking of welding seams and automatic trajectory adjustment. Therefore, welding robots based on visual sensors have been greatly developed [1].

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Welding robots equipped with visual perception systems have advantages that artificial teaching robots and offline programming robots do not have. Through the visual sensing system, changes in the welding seams can be sensed in time and adjustments can be made promptly and automatically. In addition, robots using non-contact measurement tools such as visual sensor systems for welding seam sensing have high applicability. Therefore, the research on the visual measurement technology and the visual sensing system that the robot vision sensors rely on has become the top priority [2].

As the accuracy requirements of welding processes increase, there is still little research on intelligent welding systems, especially adaptive welding systems based on 3D visual sensing technology. The 3D-PC data is obtained by 3D vision technology, and the obtained data is reconstructed. In order to determine the vision and location of the welding seam, the useful points are extracted. This method is extremely adaptable and stable. The PC data extracted based on 3D visual sensing technology is used to obtain the characteristics of the welding seam through a series of image processing or deep learning methods, thereby realizing the tracking of the welding seam and the automatic adjustment of the welding seam trajectory during the process, which greatly improves Anti-interference ability and accuracy of welding robot [3]. A current research focus and emerging trend in the realm of welding robots is the study of 3D-PC technology.

Therefore, this paper makes a comprehensive overview and analysis of the 3D-PC technology based on computer vision applied to welding robots. The overall structure of this article is as follows. In Chapter 2, the current main 3D measurement techniques and research progress are introduced. In Chapter 3, with a focus on the use of 3D-PC technology in welding robots, the research approaches and applications are examined from two angles: recognition and positioning of welding seam, welding seam tracking and trajectory automatic completion. Chapter 4 summarizes the full text and looks forward to prospective technology development trends.

2 Technical Background

2.1 3D Measurement Technology

At present, the 3D vision measurement technology applied to welding robots mainly includes: passive 3D measurement technology based on monocular vision or binocular stereo vision, and active 3D measurement technology based on line laser type and surface structured light type.

Monocular vision is the most basic one. The obtained image is mapped to 3D data through the principle of pinhole imaging, but it is inevitable that the environmental information and data dimension are missing in the mapping process. Although the other three technologies can directly obtain 3D data, there are also great differences. Binocular stereo vision belongs to passive 3D vision sensing technology. It realizes 3D reconstruction by processing the parallax of the overlapped part of the field of view in the two-dimensional(2D) images taken by two different cameras. However, when it is used to weld welding seams with unclear weld characteristics, the matching of the characteristic point clouds of the welding seams in the two pictures will produce large errors, which makes it difficult to meet the recognition accuracy standard and stability requirements of welding seams.

As active sensing technology, the 3D visual sensing technology of line laser and surface structured light has the advantage of directly obtaining the 3D data of weldment and welding seams compared with the former's passive sensing technology. The line laser type realizes the 3D reconstruction of the PC data on the path by establishing the pose relationship between the light plane and the camera. It is not affected by the arc and the workpiece but is greatly affected by the position of the laser stripe itself. So it has strong adaptability and robustness [4]. The surface structured light type can identify a variety of complex welding seams. It benefits from excellent effectiveness, good stability, and powerful adaptability, and provides a technical foundation for research on automated extraction of spliced welds [5].

2.2 Research Progress

Monocular vision technology and binocular vision technology as passive vision technologies are gradually being eliminated due to their limitations, while active vision technologies such as line laser and surface structured light are gradually becoming mainstream welding robot vision measurement technologies.

During the welding process, methods based on 2D vision often lose some important information in the process of obtaining weld information, such as weld position, weldment size, welding environment, etc. At the same time, these methods also produce positioning errors and error propagation from 2D to 3D data mapping. The 3D point cloud is not affected by factors such as illumination and shape, and has strong robustness and strong anti-interference, which has great research significance and prospect. Realizing automated welding of complex space welding seams is crucial because it can increase production effectiveness, welding quality, and the value of welding workers' labor.

At present, the visual sensing technology based on 3D point cloud recognition is mainly used in the recognition and positioning of welding seams, and welding seam tracking and trajectory automatic completion. The current research in these two fields will be introduced in detail below.

3 Application of 3D-PC Technology in the Realm of Welding Robots

3.1 Recognition and Positioning of Welding Seam

The 3D reconstruction of the object often requires semantic segmentation of the environment. Methods based on 2D vision often lose some important information in the process of obtaining welding seams information, such as weld location, weld size and other prior information, and even produces Positioning errors and error propagation for 2D to 3D mapping. The 3D-PC is not affected by factors such as illumination and shape, and has strong robustness and anti-interference ability, which has great research significance and prospects.

Since direct retrograde 3D-PC scanning of the environment and welding workpiece will generate a large amount of useless point cloud data, the 3D space location has to be confirmed using the 3D-PC data. Therefore, Jing et al. proposed to obtain RGB-D four-channel data directly through the Kinect V2 sensor, and then carry out 3D reconstruction. From the PC reconstruction data, the 3D position of the welding object is derived [6].

Xu et al. studied the bag-of-words vector weight assignment method and the key frame selection method with entropy constraints on the 3D reconstruction system based on Kintinuous. The test is performed on the RGB-D object reconstruction data set published by Jing. They analyzed the influence of the estimation accuracy of the camera trajectory attitude in the process of loop detection quality and the whole 3D reconstruction process. They found that the influence of 3D reconstruction on welding accuracy decreased significantly. At the same time, based on the point cloud segmentation deep learning network architecture, Xu et al. studied the different impacts of using the network's high-dimensional features and low-dimensional features in the feature encoding and propagation module on the network [7].

Based on the laser stripe image's grayscale distribution properties, Lu et al. created the ROI area. They performed 3D reconstruction of the filtered image, and then extracted useful pixels based on the improved gray center method. The PC data they obtained can be transformed to generate multiple types of welding seams. On this basis, they carried out the feature extraction of different types of welding seams and studied the feature point extraction methods based on PC technology. Finally, they summarized a more stable method of welding seams recognition [8].

For determining welding seam types and extracting welding seam positions, Sun et al. presented a combination method. This method can effectively overcome various interferences during the welding process using conventional joints, such as the presence of multiple grooves and pre-welded points in the welding seam. They have conducted a lot of research based on four typical weld types. The proposed method effectively improves the recognition accuracy of welding seam [9]. However, the 3D fold line welding seam existing in the equipment and manufacturing environment of large components still faces problems. Therefore, to find a solution to the position detection issue and pose of the starting solder joint in the process of locating the 3D folded line welding seam, Jia proposed a trajectory-based 3D folded line welding robot to swing GMAW real-time tracking. By obtaining the 2D information of the workpiece and using the 3D folded line welding seams pose estimation method extracted by the random sampling consistency (RANSAC) PC platform, the pose estimation of the starting solder joint is realized. This method solves the problem that the detection error of the initial solder joint position and the weldment position of the 3D folded line welding seam is too large. It also meets the inspection requirements and welding standards [10].

However, there is still a lack of universality among various welding seams recognition methods, and the same method cannot be applied to a variety of different welding scenarios. In order to address this issue, Chen et al. suggested a technique for detection that combines image segmentation, welding seam tracking, and welding pose estimation. The advantage of this approach is improved generalizability. In the welding environment with strong noise, the accuracy of the welding seam pose is ensured, and it is further verified that the welding seam pose detection method based on noise separation may successfully suppress tracking model drift. They confirmed through experiments that this method can complete the welding task under various welding conditions, accomplish the goal of real-time adjustment of the robot's position and attitude, and improve the welding accuracy and welding seam quality [11].

A feature extraction-based PC simplification approach was put up by Wang et al. When extracting the effective information of 3D-PC data, the edge features of the welding seam are retained by segmenting the 3D-PC. Then, the PC data based on local features is combined with the CAD mathematical model coordinate system to realize the positioning and size measurement of the welding seam. Experiments have shown that this method can effectively reduce the size error of welding seam creation and increase the accuracy of the positioning parameters of the welding seam [12].

3.2 Welding Seam Tracking and Trajectory Automatic Completion

Aiming at the complex environment of large-scale girder box welding sites, Li et al. studied welding seam tracking based on arc swing. They proposed to quickly segment the 3D-PC data of the welding seam, and then use the LOF algorithm to perform PC filtering to determine the beam's 3D pose. The robustness of this method has been confirmed by research and experiments [13].

Aiming at the problems of welding seam tracking and simultaneous extraction of multiple welding seams for medium and thick plate weldments, Geng et al. proposed an improved RANSAC multi-plane fitting algorithm based on 3D vision. The intersection position between the 3D-PC model's intersecting planes can be determined more precisely using this method, which mixes 3D-PC models. Based on this, they suggested a path-planning method based on a dihedral structure, which can enable the robot to realize automated planning of welding seam trajectory and welding posture without teaching [14].

In order to solve the welding difficulty of complex 3D space curve welding seams, a welding seam perception technique based on line structured light was proposed by Zhou et al. This approach can greatly optimize the trajectory generation. They used an improved method to extract welding seam with high precision and low noise from ordered point clouds, and used NURBS curves to achieve optimal generation of welding seam trajectories. It is proved by experiments that this method solves the welding difficulties of complex 3D space curve welding seams to a certain extent and improves welding accuracy [15].

With the continuous improvement of the requirements for the grinding accuracy of free-form surfaces, the technology of welding robots automatically generating grinding trajectories is facing higher and higher challenges. A brand-new 3D-PC-based feature-guided trajectory-generating method was put out by Feng et al. This method uses a movable average filter to fit each contour line of the 3D contour and then extracts effective feature points. They create an even 3D space curve using the B-spline fitting technique, and then calculate the posture of the welding tool through the optimized interpolation algorithm and cross-multiplication. Finally, they used the robot force control to plan the force at each prop contact point. This method reduces the error of trajectory generation and greatly reduces the time of path planning [16].

When processing large-scale weldments with small machining allowances, using PC data obtained from on-site measurements to plan paths will cause a lot of noise interference. Therefore, to address this issue, based on the 3D-PC data collected on-site, Wang et al. suggested planning and optimizing the path. They first generate a double non-uniform rational B-spline curve of the trajectory path point and the axis of a tool point, and then reduce the local mutation of the path by establishing an optimization function, thereby improving the smoothness and dexterity of the trajectory [17].

As a way to enhance the accuracy and weld tracking quality, Liu et al. proposed a reliable laser sensor-based welding seam tracking algorithm and sensor systems. This method can eliminate the position error caused by each stop of the mobile welding robot, to automatically correct the tracking track at any time. They confirmed through experiments that this method effectively improves the multi-station welding efficiency and assures the welding seam's good quality [18].

Since the geometric characteristics of different welding seams in multi-layer multi-pass (MLMP) welding are unclear and highly variable, it is impossible to track the weld points during the welding process directly. Additionally, in order to address the issues of the welding spot at the torch's end and the fluctuating weld edge during the multiple layers and multiple passes welding process, they proposed a system for automatically creating paths based on the features of welded seams to solve the problems of welding accuracy decline and poor filling quality. They believe that the welding seam stripes of each layer are composed of a set of key points. They use the FPLDN network to detect the welding seam feature points of each weld bead, and then utilize a standard estimating technique based on adaptive weighted PCA and improved RANSAC method to improve the fit of the welding seam. Finally, they further estimated the position and trajectory of the welding torch. Through research and experiments, Feng et al. proved that this method improved the accuracy of the network for feature point extraction from end to end and filled the technical gap in MLMP welding path planning and trajectory generation [19].

3.3 Discussion

Current optimization methods for 3D-PC visual reconstruction techniques differ from methods for enhancing 2D image data. The 3D-PC data enhancement method needs to design special enhancement strategies for different types of data sets, such as radar PC data sets and RGB-D data sets. At the same time, the spatial PC reconstruction of the weldment based on the 3D visual sensing technology and the identification and positioning of the weld still need to be optimized, and there are still errors in the matching of the feature points of the 3D-PC model with the physical feature points.

4 Conclusion

With the continuous advancement of automation and the intelligence of welding robots, 3D-PC technology has become the core technology to complete the welding task of complex welding workpieces. It has also become a hot topic of current research. With the continuous improvement of visual sensing technology, welding robots will have stronger adaptability and stability in a dynamic and unknown new complex environment. Through the understanding of 3D-PC vision sensing technology, the readers can gain a clearer grasp of how welding robot vision and sensing technologies will grow in the future, and help to guide the research and development of vision sensing systems for application requirements.

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